Australian Government
Department of Defence
Defence Science and
Technology Organisation

Ultrasonic Phased Arrays for the Inspection of Thick-Section Welds

R. J. Ditchburn and M. E. Ibrahim

Maritime Platforms Division
Defence Science and Technology Organisation

DSTO-TN-0911

ABSTRACT

Ultrasonic phased arrays will eventually replace conventional ultrasonic methods in many non-destructive evaluation (NDE) applications. However, the transition to phased arrays is not without its pitfalls and challenges. In this report we present a summary of the advantages and limitations of phased-array ultrasonics in NDE, with specific reference to the inspection of thick-section welds. The main advantages offered by phased arrays over conventional systems are increased sensitivity, coverage and speed. The main disadvantages are that (i) phased-array systems are more expensive to purchase, (ii) operation and data interpretation are more difficult and (iii) there can be greater difficulty in achieving good ultrasonic coupling due to the larger probe dimensions. Whilst proper training can overcome the majority of these disadvantages, the main obstacle to a faster uptake of the technology is the lack of widely accepted inspection standards and calibration blocks applicable to phased arrays.

RELEASE LIMITATION

Approved for public release

Published by

Maritime Platforms Division
DSTO Defence Science and Technology Organisation
506 Lorimer St
Fishermans Bend, Victoria 3207 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-014-620
September 2009

APPROVED FOR PUBLIC RELEASE

Ultrasonic Phased Arrays for the Inspection of Thick-Section Welds

Executive Summary

It is likely that ultrasonic phased arrays will eventually replace conventional ultrasonic methods in many non-destructive evaluation (NDE) applications. However, the transition to phased arrays is not without its pitfalls and challenges, and these must be understood before the technology is completely embraced by the NDE community.

The purpose of this report is to present a summary of the advantages and limitations of phased-array ultrasonics in NDE, with specific reference to the inspection of thick-section welds.

The main advantages offered by phased arrays over conventional systems are increased sensitivity, coverage and speed. These advantages are achieved through the ability to rapidly and repeatedly steer, focus and scan the ultrasonic beam electronically.

The main disadvantages of phased-array systems are that (i) they are more expensive to purchase, (ii) operation and data interpretation are more difficult and (iii) there can be greater difficulty in achieving good ultrasonic coupling due to the larger probe dimensions. Whilst proper training can overcome the majority of these disadvantages, the main obstacle to a faster uptake of the technology is the lack of widely accepted inspection standards and calibration blocks applicable to phased arrays.

Contents

1. INTRODUCTION.. 1

2. PRINCIPLES OF PHASED-ARRAY ULTRASONICS.. 1

3. ADVANTAGES OF PHASED ARRAYS 4
   3.1 Advantages for weld inspection 4

4. LIMITATIONS AND PRACTICAL PROBLEMS OF PHASED ARRAYS 6
   4.1 Limitations for weld inspection.. 7

5. CONCLUSION 8

6. REFERENCES 8

1. Introduction

Ultrasonic phased-array systems have been used successfully in the medical field for many decades. However, it was not until the 1990s that commercial systems for industrial applications appeared. Since that time, incremental improvements in design, greater computer processing power and reductions in cost have led to increased use and wider acceptance of this technology for industrial non-destructive evaluation (NDE).[1-5]

For NDE systems, phased arrays offer increased inspection sensitivity and coverage as well as decreasing inspection times compared with conventional ultrasonic techniques using single- and multi-element transducers. By virtue of these improvements, it is likely that ultrasonic phased arrays will eventually replace conventional methods in many NDE applications. However, the transition to phased arrays is not without its pitfalls and challenges and these must be understood before the technology is completely embraced by the NDE community.

The purpose of this report is to present a summary of the advantages and limitations of phased-array ultrasonics in NDE, with specific reference to the inspection of thick-section welds. Whilst much has been written in the scientific literature and in manufacturers' promotional material concerning the advantages of phased arrays, in this report the limitations and practical problems that are likely to be encountered when applying this technology are also included. The intention is to bring to light some of the more important technical issues that should be understood by those unfamiliar with phased-array technology. Undoubtedly, some of these limitations and practical problems will be overcome as the technology matures in the industrial NDE context.

The report is arranged as follows. In Section 2 the basic principles of phased arrays are presented. Advantages of phased arrays over conventional ultrasonic methods are given in Section 3, whilst limitations and practical problems are given in Section 4. In presenting the advantages and limitations of ultrasonic phased arrays, the significance of this technology to thick-section weld inspection is discussed and some recent relevant published references concerning phased-array inspection of welds are given. Finally, some conclusions are drawn in Section 5.

2. Principles of Phased-Array Ultrasonics

Ultrasonic NDE is a well-established inspection method to detect and size discontinuities in structural materials. Inspection using phased arrays has much in common with conventional ultrasonics, since the physics of wave propagation, reflection, refraction, mode conversion, and diffraction remain the same. It is the method of generating and receiving the ultrasonic waves that is different.[5]

An ultrasonic phased-array probe is comprised of multiple elements, usually between 32 and 128, each of which can act as a single ultrasonic transducer. The elements may be arranged in a variety of patterns, the simplest of which is a linear array. This and two other simple

arrangements are shown in Figure 1. Each element in the array can be pulsed individually or as part of a group to produce a wavefront. The multiple wavefronts produced from the elements then interfere to generate an overall wavefront or beam profile, which may be modified by varying the amplitude and timing of the excitation of each element. Software control of the amplitude and time delay for each element is achieved through what is referred to as a 'focal law'.

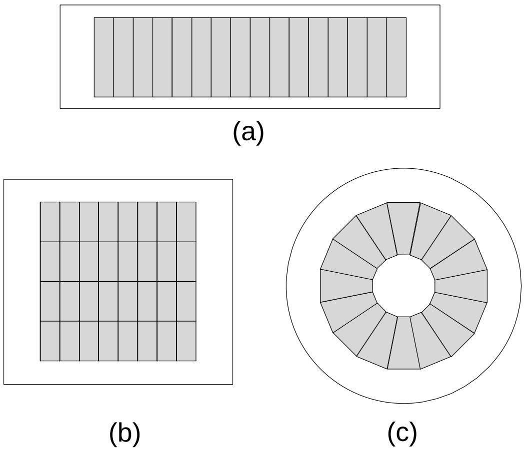

Figure 1: Examples of simple phased array element patterns. (a) A 16-element linear array, (b) a 32-element matrix, and (c) a 16-element annular array.

The ability to modify or control the beam profile generated by a phased-array probe leads to three main electronic scanning techniques that cannot be achieved using conventional ultrasonic systems. These scanning techniques are shown in Figure 2 and described below, where for simplicity it is assumed that the array elements are arranged in a linear pattern.

- *Linear scanning*
  A sub-set or group of the array elements is pulsed to form the desired beam profile and then the focal law giving this beam profile is electronically multiplexed along the length of the array (Figure 2(a)). This is the electronic equivalent of mechanically scanning a conventional (single-crystal) probe along a distance equal to the length of the larger phased-array probe. Currently, most commercially available arrays have up to 128 elements which are typically pulsed in groups of 8 to 16.
- *Dynamic depth focussing*
  By varying the focal laws the focal point is electronically moved along the nominal beam axis (Figure 2(b)).
- *Swept angular (sectorial or azimuthal) scanning*
  Focal laws are chosen to electronically steer the beam to a fixed angle of incidence, or sweep the beam through a wide angular range (Figure 2(c)).

Combinations of these electronic scanning techniques provide a far more complicated scan and greater coverage than is possible by conventional methods. These advanced scans can be programmed and modified to suit the inspection with relative ease – the operator specifies the

required beam focal distance and scan pattern, then the time delays for the elements are calculated by the software.

Ultimately, the decisions confronting the phased-array operator are the same as those when using a conventional ultrasonic system, i.e., selection of test frequency, element size, and angle of incidence.

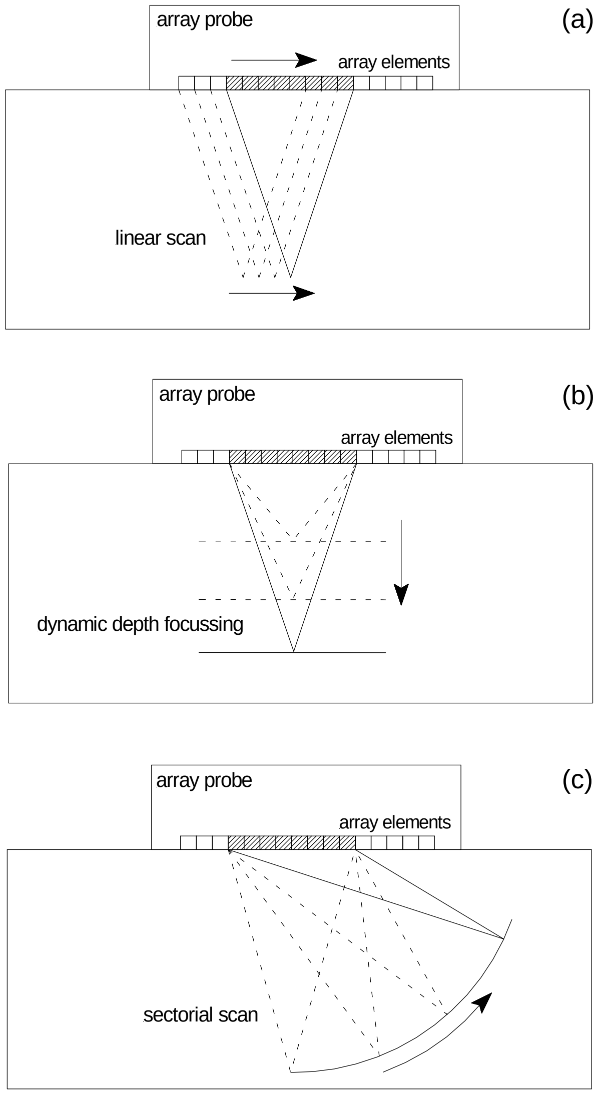

Figure 2: Diagrams showing the types of electronic scanning possible with phased-array probes: (a) linear, (b) depth focussing, and (c) swept angular (sectorial)

3. Advantages of Phased Arrays

The main advantages of ultrasonic phased arrays over conventional methods are increased inspection sensitivity and coverage, and decreased inspection times.

The first two advantages are brought about by the ability to control the direction and shape of the generated ultrasonic beam. Increased sensitivity is achieved through optimisation of the beam angle to ensure that it is perpendicular to the face of an expected discontinuity and electronic focussing allows the beam's shape and width to be optimised for an anticipated discontinuity location. Increased coverage is possible because the complex scans permitted by phased arrays allow a far greater volume of material to be interrogated from one probe position.

The third advantage, a decrease in inspection times, is achieved principally through very rapid electronic scan rates, which are many times faster and more repeatable than the mechanical scan rates of conventional methods. Furthermore, the versatility of phased-array probes means that one probe can perform multiple inspections, leading to further time savings because there is less need to change probes and reconfigure the test setup.

Another benefit of phased array systems is their ability to produce immediate images, allowing straightforward visualisation of the internal structure of a component, and simplifying data interpretation. Whilst this feature is also available in conventional instruments linked to mechanical scanning systems, it is mainly confined to large-scale or advanced systems.

3.1 Advantages for weld inspection

In addition to the advantages mentioned above, there are specific benefits in using ultrasonic phased arrays for pulse-echo shear-wave inspection of thick-section welds. The more important of these benefits are discussed below.

The geometry of a weld determines the ultrasonic inspection angles that are required. A sectorial scan enables the inspection angle to be varied and tailored to the weld geometry and is particularly useful for inspections with restricted access. A typical sectorial scan involves a stationary probe, where the beam is made to sweep through a range of angles. The scan image produced allows instant visualisation of any discontinuities detected (Figure 3).

In some inspection situations, particular discontinuity orientations are expected (e.g., transverse cracks). Phased-array systems allow the inspection angle to be set accurately and modified easily to optimise the response from a detected discontinuity.

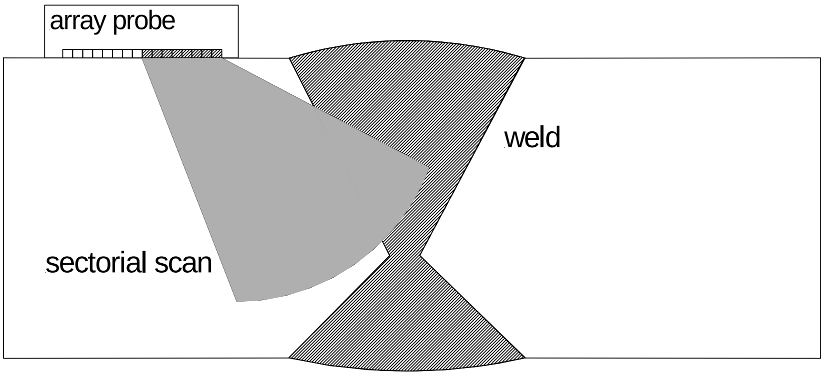

Figure 3: Diagram showing a sectorial scan of a weld

A phased-array probe is easily programmed to mimic a conventional ultrasonic weld probe, for example, a shear-wave probe to enable inspections at the commonly used angles of 45°, 60° or 70°. The benefit of phased arrays is that a single-angle inspection can be electronically multiplexed along the elements of a stationary phased-array transducer to increase weld coverage in a rapid and repeatable manner (Figure 4).

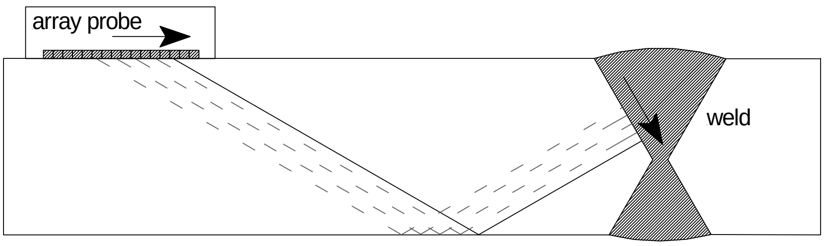

Figure 4: Diagram showing a fixed angle scan of a weld combined with an electronic linear scan to give increase weld coverage

Depending on weld and transducer dimensions, a phased-array transducer will likely need to be mechanically moved along a weld length for complete coverage – this can be done manually or automatically. By attaching an encoder to the probe head, its position can be recorded and the ultrasonic data for each position displayed. A two-dimensional array could be used to reduce or eliminate the requirement for probe movement along the weld length, however this approach must be weighed against the significantly increased cost of large two-dimensional probes, and the added difficulty of achieving good ultrasonic coupling with a large probe footprint.

When a weld discontinuity has been detected and located, inspection angles and focal spot sizes can be easily optimised for accurate sizing and improved characterisation of that particular discontinuity – resulting in improved inspection reliability. Furthermore, like a number of conventional ultrasonic systems, some phased-array systems are capable of performing time-of-flight diffraction (TOFD) inspections, which is a defect-sizing technique that is often more accurate than standard amplitude sizing methods.

4. Limitations and Practical Problems of Phased Arrays

Despite the advantages of ultrasonic phased arrays, there are limitations that a new operator needs to be aware of prior to employing this technology for non-destructive inspections. Without an appreciation of these limitations, the risk that an inspection will not reliably detect discontinuities is much greater. A useful reference for many of the practical limitations of phased arrays is given by Armitt.[6] Some of the more important limitations highlighted by him and others are summarised below.

Phased-array equipment is more complex and hence more difficult to operate than conventional instruments. A newcomer to phased arrays will often have difficulty in assimilating the wide range of data presentation modes offered by the equipment. It is also easy for an inexperienced operator to select inappropriate settings that may limit the effectiveness of an inspection. Specific formal training and experience in ultrasonic phased arrays is essential to overcome these challenges, and to ensure that the potential of the equipment is realised.

The first-time set-up is very time consuming, as the input parameters of inspection angle, focal distance and scan pattern, among others, must be determined and selected, in order to establish the focal laws. Once set up, however, the laws may be saved and quickly retrieved for subsequent inspections.

Phased-array transducers and wedges are generally quite large, so maintaining good ultrasonic coupling with the surface of the part being inspected can be difficult. Therefore, the part's surface condition and waviness is more critical for phased arrays.

Phased-array equipment is expensive, typically costing more than twice as much as a conventional system, with probes costing over five times as much as single-crystal transducers. Despite their great increase in versatility over standard transducers, one ultrasonic-array probe cannot be used to test every component. Several phased-array probes and wedges will be required in the operator's test kit to enable even routine inspections to be performed.

There is a tendency for operators to assume that a sectorial scan from a stationary probe will detect all discontinuities that exist within its sweep range. This is not correct, as the pulse-echo response depends on the angle of incidence of the ultrasound beam on the discontinuity. Clearly, not all discontinuities will be oriented at favourable detection angles. Mechanical scanning overcomes this problem by covering every part of the volume under inspection, at each incident angle in the sweep.

Focussing the beam at too shallow a depth in the material can mean that deeper discontinuities may be missed. If the entire thickness of the material is to be inspected, it is best for the focal length to be not less than the material thickness.

It is important to understand the beam profile before trying to interpret discontinuity indications. In conventional inspections, the manufacturer and operator will have

characterised each probe and the beam profile is therefore known. The beam profile of a phased-array transducer is adjustable and changes with any alteration to the focal laws. Before attempting to perform sizing measurements, the relevant phased-array beam profile should be measured or at least calculated.

Two important impediments to the faster take-up of phased-array ultrasonics are the absence of widely accepted (i) phased-array inspection standards and (ii) calibration blocks. In 2008, *ASTM International* issued a standard containing procedures for the evaluation of some performance characteristics of phased-array ultrasonic instruments and systems.[7] However, standards specifically for phased-array inspections are needed. At present, a number of calibration blocks are employed by various organisations around the world for their own purposes. Achieving conformity with calibration blocks will mean that any new inspection standards written are more widely applicable and foster a quicker adoption of the technology.

4.1 Limitations for weld inspection

In addition to the limitations mentioned above, there are specific limitations in the application of ultrasonic phased arrays for pulse-echo shear-wave inspection of thick-section welds. Some of the more important limitations related to weld inspection are summarised below.

The weld inspection community has begun to address the two issues mentioned in Section 4 that are delaying the take-up of ultrasonic phased arrays. At *ASTM International*, work is underway to develop a standard to describe techniques for inspecting welds using ultrasonic phased-array methods.[1] In the UK, the Ministry of Defence's Defence Standard 02-729[8] describes phased-array inspection methods in some detail and a gives a suggested calibration block design. The *International Institute of Welding* currently has a working group designing a block specifically applicable to weld inspection – recommendations from this group are expected during 2009.

Another obstacle to the take-up of phased arrays is the lack of suitably trained and certified phased-array operators. The inherent complexity of phased-array systems means that even the most experienced weld inspectors need to undertake comprehensive formal training to better place them to perform reliable inspections and avoid some of the pitfalls mentioned in this report.

Given that the selection of angle of incidence is so important in the inspection of welds, it is worth repeating the point made in Section 4 above concerning the wrong perception[6] that one wide-angled sectorial scan will detect all discontinuities in the weld. Since the ultrasonic response will depend on the (i) angle of incidence on the discontinuity, (ii) location of the array and (iii) thickness of the plate, many discontinuities will not be oriented at favourable angles to be detected. Consequently, fixed-angle scans should be used to inspect the fusion faces of a weld to ensure that the beam is maintained normal to the weld-preparation angle. In effect, this approach mimics a conventional inspection, but with the benefit of being able to configure other beam profiles to achieve greater coverage within the weld volume.

---

[1] Draft document under development by subcommittee E07.06, *ASTM WK20531 New practice for contact ultrasonic testing of welds* (ASTM International)

5. Conclusion

A summary of the important advantages and limitations of phased-array ultrasonic NDE has been presented, with specific reference to the inspection of thick-section welds. The main advantages offered by phased arrays over conventional systems are: increased inspection sensitivity; increased coverage and decreased inspection costs. These advantages are achieved through the ability to rapidly and repeatedly steer, focus and scan the ultrasonic beam electronically. The main disadvantages of phased-array systems are that (i) they are more expensive to purchase, (ii) operation and data interpretation are more difficult and (iii) there can be greater difficulty in achieving good ultrasonic coupling due to the larger probe dimensions. Whilst proper training can overcome the majority of these disadvantages, the main obstacle to a faster uptake of the technology is the lack of widely accepted inspection standards and calibration blocks applicable to phased arrays.

6. References

[1] *Introduction to Phased Array Ultrasonic Technology Applications: R/D Tech Guideline* (Olympus NDT, Waltham, 2004).

[2] *Nondestructive Testing Handbook: Ultrasonic Testing*, Vol. 7, 3 ed. (American Society for Nondestructive Testing, Columbus, 2007).

[3] *Advances in Phased Array Ultrasonic Technology Applications* (Olympus NDT, Waltham, 2007).

[4] B. W. Drinkwater and P. D. Wilcox, Ultrasonic arrays for non-destructive evaluation: A review, NDT&E Int. **39**, 525 (2006).

[5] V. Lupien, Principles of phased array ultrasound for nondestructive testing, Mater. Eval. **65**, 24 (2007).

[6] T. Armitt, in *Proceedings of 9th European Congress on Non-Destructive Testing (ECNDT 2006)*, Berlin, 2006.

[7] *ASTM E2419-08 Standard guide for evaluating performance characteristics of phased-array ultrasonic testing instruments and systems* (ASTM International, West Conshohocken, 2008).

[8] Ministry of Defence, Defence Standard 02-729 "*Requirements for Non-Destructive Examination Methods," Part 5: Ultrasonic*, 2006).

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
DOCUMENT CONTROL DATA

1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)

2. TITLE Ultrasonic Phased Arrays for the Inspection of Thick-Section Welds	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) R. J. Ditchburn and M. E. Ibrahim	5. CORPORATE AUTHOR DSTO Defence Science and Technology Organisation 506 Lorimer St Fishermans Bend Victoria 3207 Australia

6a. DSTO NUMBER DSTO-TN-0911	6b. AR NUMBER AR-014-620	6c. TYPE OF REPORT Technical Note	7. DOCUMENT DATE September 2009

8. FILE NUMBER 2009/1083096	9. TASK NUMBER NAV 07/119	10. TASK SPONSOR DGSM	11. NO. OF PAGES 8	12. NO. OF REFERENCES 8

13. URL OF ELECTRONIC VERSION http://dsto.defence.gov.au/corporate/reports/DSTO-TN-0911.pdf	14. RELEASE AUTHORITY Chief, Maritime Platforms Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO RESEARCH LIBRARY THESAURUS http://web-vic.dsto.defence.gov.au/workareas/library/resources/dsto_thesaurus.shtml

Non-destructive testing, ultrasonics, phased-array ultrasonics, inspection, structural integrity

19. ABSTRACT
Ultrasonic phased arrays will eventually replace conventional ultrasonic methods in many non-destructive evaluation (NDE) applications. However, the transition to phased arrays is not without its pitfalls and challenges. In this report we present a summary of the advantages and limitations of phased-array ultrasonics in NDE, with specific reference to the inspection of thick-section welds. The main advantages offered by phased arrays over conventional systems are increased sensitivity, coverage and speed. The main disadvantages are that (i) phased-array systems are more expensive to purchase, (ii) operation and data interpretation are more difficult and (iii) there can be greater difficulty in achieving good ultrasonic coupling due to the larger probe dimensions. Whilst proper training can overcome the majority of these disadvantages, the main obstacle to a faster uptake of the technology is the lack of widely accepted inspection standards and calibration blocks applicable to phased arrays.